4.0 RADIOLOGICAL STATUS OF THE FACILITY

The radiological status of the DU Impact Area at JPG has been determined from historical records, a radiological scoping survey conducted in 1994 (SEG 1995a,b), and a radiological characterization survey conducted in 1995 (SEG 1996). Section 4.1 presents a summary of historical information relevant to radiological characterization of the JPG and a description of the methods, procedures, and results of a final status survey of facilities and grounds located south of the firing line. Section 4.2 describes the methods and procedures used in scoping and characterization studies that determined the radiological status of the DU Impact Area. Section 4.3 summarizes the results of the radiological characterization of the DU Impact Area. A summary of the facility's radiological status is presented in Section 4.4.

4.1 HISTORICAL SITE ASSESSMENT

Historical information relevant to termination of the current license includes the facility operating history, characterization of radioactive material used at the facility, characterization of support facilities, and monitoring of radioactive material in the environment. The following paragraphs summarize these sources of information. The facility operating history is described in more detail in Section 2.0 of this DP.

4.1.1 Summary of Facility Operating History

Testing of conventional explosives was conducted at JPG between 1941 and 1994. NRC-licensed activities, including handling and test firing of tank penetrator rounds containing DU, were conducted between 1984 and 1994. All firings of DU were conducted from three gun positions designated as Firing Points J, 500 Center, and K, and were directed toward the DU Impact Area. Adjacent firing points and their northward-oriented firing lines are separated by a distance of approximately 394 ft (120 m). Masses of DU fired from Firing Points J, 500 Center, and K were 14,550, 196,886, and 8,572 lbs [6,600, 89,306, and 3,888 kg], respectively. During active testing of DU munitions, explosives ordnance personnel periodically would sweep the range area surrounding the DU target area to recover DU. The recovered projectiles and fragments were weighed and the recovered weights subtracted from the fired projectile weights to determine the total DU material weight remaining in the range. The mass of DU remaining in the DU Impact Area is estimated as 154,323 lbs (70,000 kg).

DU projectiles were fired from tank guns at high velocities against soft cloth targets. Upon impact, the projectiles penetrated into the earth, ricocheted, or broke into two or more pieces rather than shattering into small particles (Mason and Hanger 1992). Firing of DU projectiles against metal target plates, which could contribute to minute particle fragmentation or aerosolization of DU rods and particle burning, was not conducted.

4.1.2 Characterization of Radioactive Materials

Radioactive materials utilized at JPG were in the form of DU penetrators contained in 105 or 120 millimeter (mm) antitank cartridges. The penetrators themselves were long, thin cylinders of DU alloyed with titanium (0.75 percent) and contained no explosive materials. Original masses of the penetrators were approximately 8.5 and 10.7 lbs (3.9 and 4.9 kg) while nominal diameters and lengths were 1.2 and 12.6 in. (3 and 32 cm), respectively. In addition to use in performance testing, DU munitions were used in combat in the Gulf war (1991) and in the Balkans conflict (1999). The penetrators contain the naturally occurring isotopes of uranium and low concentrations of transuranic (TRU) elements and fission products derived from use of recycled uranium in the gaseous diffusion plants (GDPs) that produced enriched uranium and DU. Concentrations of the uranium (U) isotopes U-234, U-235, U-236, and U-238 in DU used by the U.S. Department of Defense (DoD) have been reported as 0.0006, 0.2,

0.0003, and 99.8 percent, respectively [Center for Health Promotion and Prevention Medicine (USACHPPM) 2000]. At these concentrations, total specific activity is 3.8×10^{-7} curies per gram (Ci/g). Further information on radiological characterization of the penetrators is available from several sources:

- specifications developed during operation of the GDPs,
- review of the flow of recycled uranium through the DOE complex,
- analysis of billets used in the production of armor containing DU, and
- analysis of penetrators used in the Balkans conflict.

The following discussion summarizes data and results from these information sources.

The presence of TRU elements in the Paducah, Kentucky, GDP was recognized as early as 1953 and confirmed in 1957 (DOE 2000a). At this plant, a neptunium (Np) recovery project was begun in 1958, and a technetium (Tc) recovery program was operated from 1960 to 1963. As early as 1953, plant documents identified a plutonium concentration of 10 parts per billion (ppb) of uranium as acceptable feed material. Plant documents, dated 1966, specified the maximum level of alpha activity from reactor fuel elements as 150 disintegrations per minute per gram (dpm/g) of uranium. This level was interpreted as equivalent to concentrations of 0.0004, 1.0, or 0.3 ppb of uranium for plutonium-238 (Pu-238), Pu-239, or Pu-240, respectively. A 1957 plant document indicates that this maximum specification was increased to 1,500 dpm/g of uranium in 1967, and the Neptunium-237 (Np-237) limit became 1 part per million (ppm) uranium basis. Between 1986 and 1989, the feed specification for plutonium was 10 ppb of uranium. After 1989, the feed specification for plutonium and neptunium combined became 200 dpm/g of uranium. This limited feed concentrations to 1.4 and 125 ppb of uranium for Pu-239 and Np-237, respectively.

As part of an effort to assess the health risks for workers at the Paducah GDP, the U.S. Department of Energy (DOE) completed a study of the mass flows and radiological characteristics of recycled uranium processed within the DOE complex (DOE 2000b). While the flow of recycled material within the complex was complicated, the study estimated that as much as 143,298 short tons (130,000 metric tons) of recycled uranium were produced in separation plants and that blending and other operations increased the quantity of uranium containing recycled material to 275,572 short tons (250,000). Based on measurement data and the results of mass balance projects conducted for the GDPs, DOE estimated the contaminant levels summarized in Table 4-1. Measurements of contaminant levels in DU processed in the Specific Manufacturing Facility at the Idaho National Engineering and Environmental Laboratory (INEEL) are summarized in Table 4-2.

The Tank-Automotive and Armaments Command (TACOM) of the U.S. Army has an NRC license governing management and use of DU in armor. To fully describe in the license the radiological characteristics of the DU armor, TACOM, at the request of the NRC, performed a sampling and laboratory analysis to establish concentrations of Tc and TRU elements in DU used in the armor. TACOM analyzed random samples from three generations, or populations, of finished billets (Bhat 2000). The first population was drawn from billets comprising an original shipment of DU. The second population comprises billets cast from scrap material of the first population, while the third population comprises billets cast from scrap material of the second population. Samples were collected by drilling approximately 0.088 lb (40 g) of shavings from each of 20 billets of the first population, 30 billets of the second population, and 10 billets of the third population. The samples were dissolved in nitric acid and analyzed for TRU elements using alpha and mass spectroscopy. A set of duplicate samples was selected and analyzed independently for quality assurance (QA) purposes. The results of the analysis are summarized in Table 4-3. The nuclides Pu-236, Pu-242, and Americium-243 (Am-243) were not present above the minimum detectable concentration of 0.2 pCi/g of uranium. In addition to the above analyses, gamma spectroscopy was to investigate the presence of fission products other than Tc. The analysis identified no gamma peaks other than those due to progeny of uranium.

Table 4-1. Summary of Constituents in Product and Tails Streams at the GDPs

Site	Radionuclide	Concentration (ppb)	
		Enriched Product	Depleted Tails
Oak Ridge	Pu	< 0.05	< 0.01
	Np	< 5	< 5
	Tc	< 1,000	< 10
Portsmouth	Pu	< 0.037	< 0.007
	Np	< 3.19	< 0.6
	Tc	< 690	< 0.4
Paducah	Pu	< 0.01	< 0.01
	Np	< 5	< 5
	Tc	< 20,000 (?)	< 10

Source: DOE 2000a.
GDP = gaseous diffusion plant.
Np = Neptunium.
ppb = parts per billion.
Pu = Plutonium.
Tc = Technetium.

Table 4-2. Representative Sampling of Contaminants in DU at INEEL

Nuclide	Concentration (ppb)		
	Maximum	Minimum	Average
Np-237	5.29	1.62	2.58
Pu-238	1.2×10^{-4}	0	1.59×10^{-5}
Pu-239/240	0.0428	0	6.55×10^{-3}
Am-241	5.61×10^{-3}	0	8.1×10^{-4}
Tc-99	31.6	3.78	9.06

Source: DOE 2000b.
DU = depleted uranium.
INEEL = Idaho National Engineering and Environmental Laboratory.
Np = Neptunium.
ppb = parts per billion.
Pu = Plutonium.
Tc = Technetium.

Table 4-3. Concentrations of Contaminants in Billets of DU Armor

Nuclide	Concentration, ±1 sigma (pCi/g armor)					
	Population No. 1		Population No. 2		Population No. 3	
	Lowest Value	Highest Value	Lowest Value	Highest Value	Lowest Value	Highest Value
Am-241	–0.8 ±1.3	4.4 ±5.5	–1.7 ±2.8	19 ±5.8	1.2 ±1.8	5.3 ±2.2
Np-237	< 1.3	3.7 ±0.92	< 1.1	2.2	1.2	< 3.6
Pu-238	–0.03 ±0.06	2.0 ±0.53	0.01 ±0.01	0.80 ±0.14	0.17 ±0.06	0.86 ±0.23
Pu-239/240	–1.2 ±1.9	2.7 ±0.88	0.12 ±0.17	1.0 ±0.16	0.24 ±0.06	0.86 ±0.14
Tc-99	< 73	240 ±47	64	540 ±32	83	400 ±26

Source: Bhat 2000.
Am = Americium.
Np = Neptunium.
pCi/g = picocuries per gram.
Pu = Plutonium.
Tc = Technetium.

Following termination of hostile actions in the Balkans during the early 1990s, a United Nations Environmental Programme (UNEP) conducted an assessment of the impact of the Kosovo conflict on the environment and human settlements. As an element of this program, soil, water and other samples were collected from 11 sites where DU had reportedly been used in the conflict (UNEP 2001). Analysis of environmental samples showed low levels of contamination but identified U-236 at concentrations in the range of 61,000 to 71,000 becquerels per kilogram (Bq/kg). Identification of U-236 indicated the presence of recycled DU, motivating further analysis for TRU elements. The results of the analysis of four penetrator samples are summarized in Table 4-4.

Table 4-4. Studies on Penetrators from the Kosovo Conflict

Sample Number/ Found At	Concentration (Bq/kg) [Ci/g]				
	U-238	U-235	U-234	U-236	Pu-239/-240
ZA/R-00-505-01 Ceja Mountain	$12.37 \times 10^{+6}$ 3.34×10^{-7}	$1.60 \times 10^{+5}$ 4.32×10^{-9}	$1.16 \times 10^{+6}$ 3.14×10^{-8}	$6.10 \times 10^{+4}$ 1.65×10^{-9}	< 0.8 $< 2.16 \times 10^{-14}$
ZA/R-00-505-02 Ceja Mountain	$12.37 \times 10^{+6}$ 3.34×10^{-7}	$1.61 \times 10^{+5}$ 4.35×10^{-9}	$1.51 \times 10^{+6}$ 4.08×10^{-8}	$6.15 \times 10^{+4}$ 1.66×10^{-9}	2 5.41×10^{-14}
Kokovce	$12.70 \times 10^{+6}$ 4.43×10^{-7}	$2.00 \times 10^{+5}$ 5.41×10^{-9}	$1.55 \times 10^{+6}$ 4.19×10^{-8}	$5.72 \times 10^{+4}$ 1.55×10^{-9}	< 0.8 $< 2.16 \times 10^{-14}$
Ceja Mountain	NR	NR	NR	NR	12.9 3.49×10^{-13}

Source: UNEP 2001.
Bq/kg = becquerel per kilogram.
Ci/g = curies per gram.
NR = Data not reported. Note to Author: What does blank in Ceja Mountain mean for the isotopes of U?
Pu = Plutonium.
U = Uranium.

4.1.3 Final Status Survey of Support Facilities

Support facilities used in licensed activities at JPG included 17 buildings and storage facilities (magazines) located south of the firing points (the firing line) and the three firing points. A final survey of these support facilities was conducted in late 1994 and early 1995 in conjunction with decontamination of these facilities (SEG 1995a,b). The results of the survey supported release with no restrictions of the buildings and magazines from the JPG license. Criteria applicable at the time included limits on surface contamination of beta and alpha emitters, exposure rate, and uranium concentration in soil (NRC 1987).

Based on historical site information, facilities were grouped as "affected" or "unaffected." The survey identified three structures (Building 610, Building 611, and the Portable Magazine) containing eight areas where direct DU surface contamination exceeded applicable NRC requirements. Prior to decontamination, the maximum measured surface contamination ranged from 28,000 disintegrations per minute (dpm)/100 square centimeters (cm^2) to 158,000 dpm/100 cm^2. The applicable NRC requirement is 15,000 dpm/100 cm^2 for maximum surface contamination from uranium or beta emitters. The DU contamination in these eight areas was attributable to the storage of DU penetrators retrieved from the firing range. Remediation of all measured contaminated surfaces in the eight areas was accomplished by a combination of scabbling, jack hammering, and using a needle-gun to remove contaminated material. This remediation process resulted in the generation of six 55-gallon drums of waste equivalent to a total waste volume of 1.3 cubic meters (m^3) [45 ft^3], which were sealed, surveyed, and placed in temporary storage pending disposal. The remaining 14 buildings and the 3 firing points were classed as unaffected.

After remediation, a final survey of both affected and unaffected facilities was performed to demonstrate that all surfaces met the NRC requirements of 15,000 dpm/100 cm^2 and 5,000 dpm/100 cm^2 for maximum and average uranium or beta contamination. Differing approaches were used for affected and unaffected facilities. For affected facilities, 100 percent of all areas were grided and scanned, and 5 points within each grid were surveyed for beta-gamma contamination. For unaffected facilities, 10 percent of all areas were scanned, and a minimum of 30 randomly selected locations were surveyed for total and removable activity. A total of 6,426 swabs and beta surface measurements were made on surfaces for all the previously identified structures. The highest maximum measured value for any area was 3,901 dpm/100 cm^2, which is well below (74 percent) the associated NRC limit of 15,000 dpm/100 cm^2. The highest average measurement for any area was 805 dpm/100 cm^2, which is also well below (84 percent) the associated NRC limit of 5,000 dpm/100 cm^2. In addition, 10 soil samples were collected and analyzed for uranium isotopic distribution for each firing point. The average total uranium concentrations in soil were 1.5, 11.8, and 1.3 pCi/g for Firing Points J, 500 Center, and K, respectively.

A total of 1,040 gamma dose rate measurements in previously contaminated structures were made after remediation, with the highest structure individual measured values being 14.0 microroentgen per hour (14.0 μR/hr) for an average measured value, and 20.8 μR/hr for a maximum measured value. Both of these values were well below (< 10 percent of the limit) their respective NRC limits of 200 microrad per hour (μrad/hr) for average dose rate and 1,000 μrad/hr for maximum dose rate.

For the measurement of building and soil DU contamination, a Ludlum Model 2350 Data Logger™ was used with one of the following three detectors: (1) 15.5 square inch ($in.^2$) [100 cm^2] gas-flow proportional detector (Ludlum Model 43-68™) for direct beta measurement and scanning; (2) 1-in. by 1-in. (2.54-cm by 2.54-cm) sodium iodide (NaI) NaI(Tl) high-energy gamma scintillation detector (Ludlum Model 44-2™) for gamma exposure rate measurements; and (3) Geiger-Muller (G-M) detector (Ludlum Model 44-40™), with the proportional detector, for contamination smear measurements.

All instruments were calibrated in accordance with American National Standards Institute, Inc. (ANSI) N323-1988 and ANSI N42.17A-1989 using sources traceable to the National Institute of Standards and

Technology (NIST). The proportional and G-M detectors were calibrated twice daily with a Tc-99 source, while the NaI detector was calibrated twice daily with a cesium-137 (Cs-137) source. All detectors were calibrated so that they were determined to be within ±20 percent of the actual source. Appropriate SEG quality assurance and quality control (QA/QC) procedures were used for the survey.

4.1.4 Environmental Radiation Monitoring Program

An environmental monitoring program, termed the Environmental Radiation Monitoring (ERM) Program, has been implemented at JPG from 1983 to the present. For the period from 1983 to 1994, samples located on a judgmental basis have been collected for up to 58 soil, 11 groundwater, and 11 surface water and sediment locations. In addition, results from analysis of 17 vegetation and approximately 25 wildlife samples have been reported (Ebinger and Hanson 1996).

Under the current ERM Program, 4 soil, 11 groundwater, and 8 surface water and sediment locations are sampled (U.S. Army 2002). The four soil locations are at the corners of the DU Impact Area. Groundwater samples are collected at the same locations as those of the scoping and characterization surveys (Figures 4-1 and 4-2). Four surface water samples are collected on Big Creek, three in the DU Impact Area and one at the west perimeter fence. Four surface water samples are collected on Middle Fork Creek, one at the southeast corner of the DU Impact Area, two in the Firing Line area, and one at the west perimeter fence. Sediment samples are collected at the same locations as the surface water samples.

4.2 METHODS AND PROCEDURES FOR SURVEYS OF THE DU IMPACT AREA

The methods and procedures used in the scoping and characterization surveys of the DU Impact Area are described in Sections 4.2.1 and 4.2.2, respectively. These descriptions are based on the SEG reports (SEG 1995a,b; SEG 1996). Results of the surveys are presented in Section 4.3.

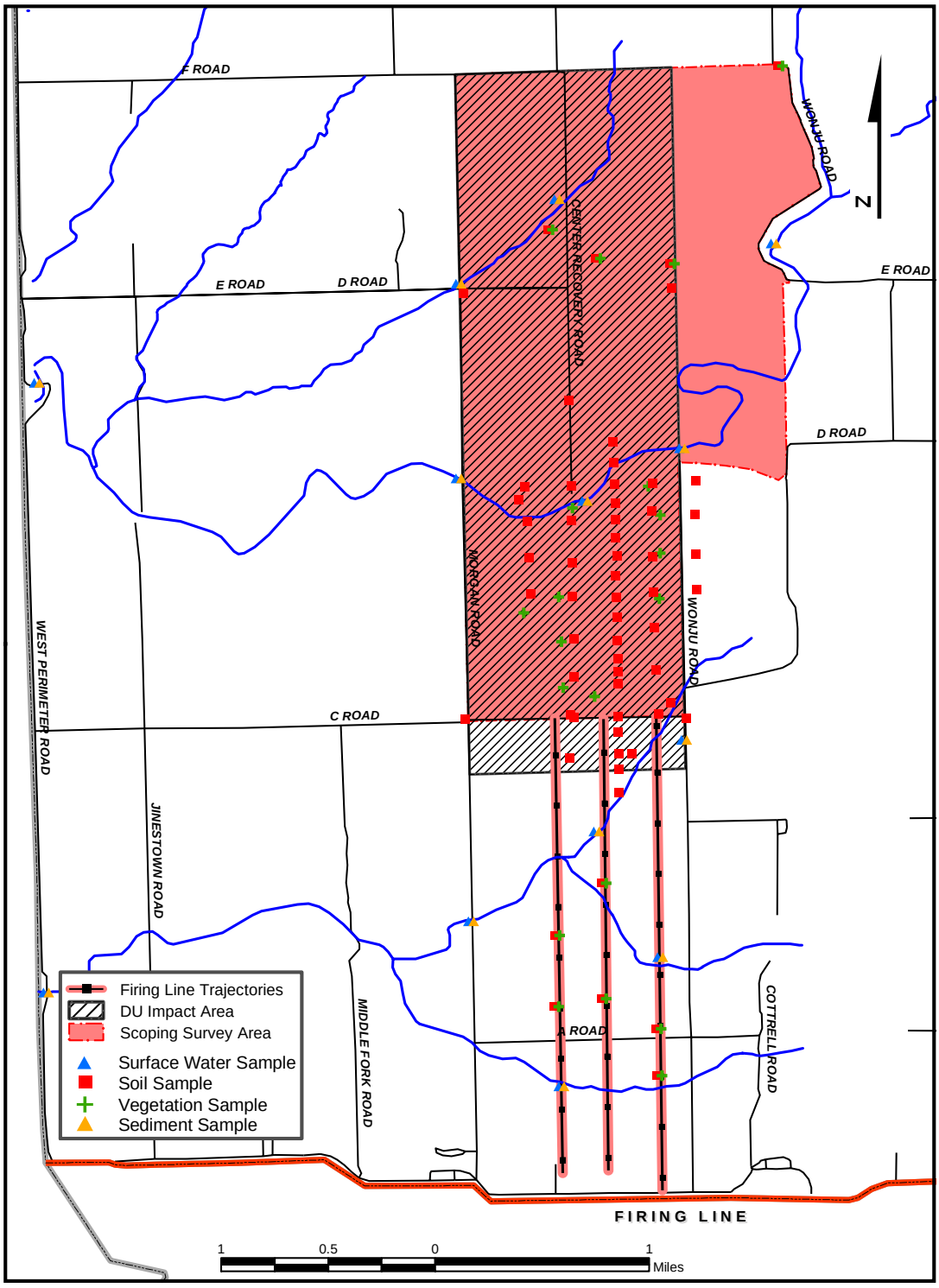
4.2.1 Scoping Survey

Areas potentially affected by facility operations include the firing lines and the DU Impact Area. A radiological scoping survey of these areas was conducted between October 8 and December 23, 1994. The objective of the study was to confirm and document areas affected by DU projectiles and to identify areas to be included in further studies (SEG 1995a).

The survey was conducted according to a site-specific plan and procedures. The procedures included identification of instrumentation requirements and development of data quality objectives (DQOs) and methods for sample collection and measurement and data reduction and evaluation. The approach to data collection involved measurement of exposure rates at grid locations and collection of soil, groundwater, surface water, sediment, and vegetation samples at locations referenced to a similar grid.

For exposure rate measurements in the DU Impact Area, grid lines were established at separations of 164 ft (50 m) in the north-south direction, and measurements were taken 3.3 ft (1 m) above the ground at 33-ft (10-m) intervals along each grid line. For the exposure rate measurements in the firing line area, three north-south grid lines were established for each of the three firing lines. A central grid line was located along the firing line, and two additional grid lines were located 164 ft (50 m) to the east and west of the central line. Exposure rate measurements were taken 3.3 ft (1 m) above ground level at an interval of 33 ft (10 m) along each grid line.

Soil, groundwater, surface water, sediment, and vegetation samples were collected on a judgmental basis determined, in part, by locations used in the environmental monitoring program. A total of 62 soil, 11 groundwater, 14 surface water, 13 sediment, and 20 vegetation locations were sampled. Sampling locations are summarized in Figure 4-1.



Source: SEG 1995.

Figure 4-1. Scoping Survey Sample Locations
Jefferson Proving Ground, Indiana (Scoping area survey color and area on map?)

Exposure rates were measured using a Ludlum Model 44-2™ (1-in. by 1-in.) NaI detector in conjunction with a Ludlum Model 2350 Data Logger™. Detectors and data loggers were calibrated using NIST-traceable sources and calibration equipment. Calibration checks were conducted at the beginning and end of each workday. Environmental samples were packaged, surveyed, and shipped to an approved vendor for alpha spectroscopy isotopic analysis. A chain-of-custody (COC) record was completed for each shipment. Minimum detectable concentrations less than 0.3, 0.07, and 0.06 pCi/g and 0.5 picocuries per liter (pCi/L) were reported for soil, sediment and vegetation, and water samples, respectively (SEG 1995a).

Prior to performance of exposure measurements in the DU Impact Area, a background study was performed. Thirty-five locations south of the firing line were measured to determine an average background exposure rate of 12 μR/hr. The result is consistent with results of the site environmental monitoring program.

4.2.2 Characterization Survey

The scoping survey conducted in late 1994 confirmed classification of the DU Impact Area as a radiologically affected area. Additional information on residual contamination in the DU Impact Area was collected in a characterization study conducted in mid-1995. The purpose of the characterization survey was to confirm and document the contamination in a 1,300-acre (5.3-km^2) portion of the DU Impact Area and to estimate costs and techniques for decontamination of the area.

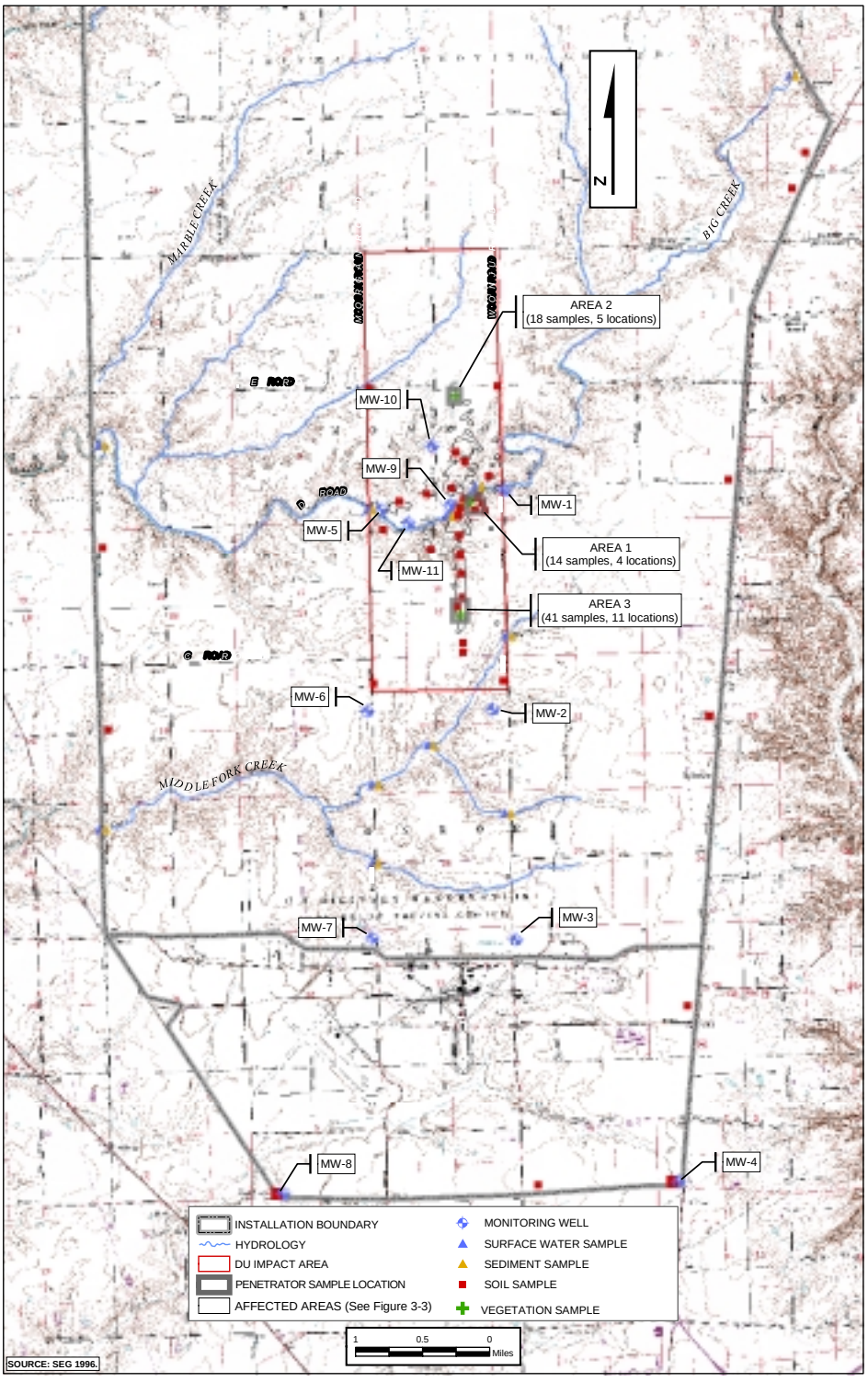
The survey design utilized a combination of random- and judgment-selected locations to estimate the size of the affected area and the volume of contaminated soil and to confirm prior results of environmental sampling. Estimation of the volume of contaminated soil involved establishing the depth profile of contamination and development of a correlation between level of contamination in soil and exposure rate. Locations selected based on best judgment included:

- Background soil samples: 10 locations to match the environmental baseline;
- Penetrator soil samples: 20 locations beneath DU penetrators;
- 500 Center trench exposure rate measurements: 10 locations in 33-ft by 33-ft (10-m by 10-m) grids traversing west to east across the 500 Center trench;
- Vegetation samples: 10 locations within 3 ft of the first 10 penetrator soil samples;
- Groundwater samples: 11 locations of completed wells;
- Surface water: 10 locations determined by configuration of existing streams;
- Sediment samples: 10 locations to match surface water sampling locations; and
- Biological samples: clams, fish, turtle, and deer at locations of convenience.

Locations randomly selected included:

- 20 soil locations in the DU Impact Area, and
- 20 exposure rate/gamma spectroscopy measurements of 33-ft by 33-ft (10-m by 10-m) grids.

Sampling locations for the characterization survey are summarized in Figure 4-2. In the case of background, random, and judgmental locations for soil, samples were collected at three depths: 0 to 5.9 in., 5.9 to 11.8 in., and 11.8 to 17.7 in. (0 to 15 cm, 15 to 30 cm, and 30 to 45 cm). Samples of soil, groundwater, surface water, sediment, fish, freshwater clams, and turtle were analyzed using alpha spectroscopy to determine concentrations of U-234, U-235, U-238, and the ratio of concentration of U-234 to U-238.



Source: SEG 1996.

Figure 4-2. Characterization Survey Sample Locations
Jefferson Proving Ground, Indiana

Integrated exposure rate measurements and in situ gamma spectroscopy was performed for the thirty 33-ft by 33-ft (10-m by 10-m) square grids. Two exposure rate measurements were made at each location: 120-second integrated count while walking over the 33-ft by 33-ft (10-m by 10-m) grid and a 60-second integrated count at the same location where soil samples were taken. The Ludlum Model 2350™ was used with a 1-in. by 1-in. (2.44-cm by 2.44-cm) NaI detector. Exposure rate data were downloaded from the Ludlum Data Logger™ to a personal computer for storage and comparison.

In situ gamma spectroscopy, using the Canberra System, includes a 2-in. by 2-in. (5.08-cm by 5.08-cm) high-purity germanium crystal with a 5-day-duration liquid nitrogen coolant supply, an IBM "Thinkpad" notebook computer, and a laboratory-grade, multi-channel analyzer for real-time radionuclide concentration analysis.

To measure DU concentrations, two U-238 radionuclide decay products were evaluated as effective indicators because they are both in equilibrium with U-238, the major constituent of DU: thorium-234 (Th-234) and protactinium (Pa-234m). Although the yield for Th-234 is greater than that of Pa-234m, the gamma ray emitted by Th-234 [0.093 megaelectron volt (MeV)] is much smaller than that of Pa-234m (1.08 MeV). The low gamma energy of Th-234 makes it much more difficult to detect especially when considering attenuation from soil, whereas the approximately ten times higher gamma rays from Pa-234m enable it to be detected. Therefore, the measurement of Pa-234m was used to determine U-238 and DU concentration.

To determine whether the measured uranium present was due to DU or natural uranium, the U-238/U-234 ratio was determined by measuring the concentration of each of these isotopes. A U-238/U-234 ratio of two or less is representative of natural uranium, whereas higher ratios are indicative of DU. This difference in ratio is due to the fact that the relative abundance of U-238 in DU has been significantly increased after U-235 has been removed from natural uranium since much of the U-234 has been concentrated with the U-235. In addition, the much smaller half-life of U-234, as compared to U-238, results in a much higher specific activity of U-234 even though its natural abundance in uranium is only approximately 0.005 percent as compared to U-238 at > 99 percent. Four other independent studies of the U-238/U-234 ratio in soil and water resulted in measured ratio values of 0.8 to 2.0 for soil and 0.025 to 2.0 for water (Fujikawa et al. 2000; Gilkeson and Cowart 1987; Goldstein et al. 1997; Osmond and Cowart 1976).

It is important to note that no areas or surfaces within the 1,300-acre (5.3-km^2) JPG DU Impact Area were inaccessible for this survey. Due to the potential presence of UXO, suitable precautions were taken in the field to prevent the occurrence of any accidents involving such UXO. The only other hazard present, which did not hinder the conduct of the survey, was the presence of sometimes rugged and steep terrain.

The characterization survey used three principal instruments at the JPG site: Ludlum Model 2350 Data Logger™, Ludlum Model 44-2 Sodium Iodide NaI(Tl)™ detector, and Canberra InSpector™ gamma spectroscopy system. The two Ludlum instruments were used to measure and record exposure rates while the Canberra system was used on-site to measure gamma ray-emitting radionuclide concentrations in soil samples. An off-site lab was used for alpha spectroscopy. All instruments were calibrated semi-annually by Ludlum Measurements, Inc., using NIST-traceable sources and calibration equipment. At the beginning and end of each workday, daily calibration checks were conducted with all instrumentation.

This survey was conducted under the controls and protocols of the SEG QA/QC Programs and Procedures. The calibration, maintenance, accountability, operation, and QC of radiation detection instruments were performed in accordance with procedures that implement the guidelines in ANSI N323-1978 and ANSI N42.17A-1989. Each survey measurement was handled and documented using appropriate and unique identifying numbers. Off-site sample shipments were accompanied by a COC

record to track each sample. Replicate laboratory analysis was performed by Lockheed Analytical Services on selected samples. Method blanks were analyzed at a frequency of 5 percent per batch. Each batch of up to 20 samples had an independent laboratory control sample (LCS) prepared and included. One duplicate sample was prepared for each ten samples in a batch.

Analysis of the measurement methodology, instrumentation, and data provides ample evidence of the adequacy of the survey for the following reasons: (1) The Ludlum instrumentation used was specifically designed for this application, has the appropriate sensitivity for gamma radiation energy in the range of interest for Th-234 and Pa-234m, and has an acceptable manufacturer-designated accuracy of ±10 percent; (2) the Canberra instrumentation has been extensively used for in situ radionuclide concentration measurement in soils and has been validated by the Monte Carlo N-Particle (MCNP) radiation transport digital computer code to substantiate an accuracy of ±10 percent for in situ soil measurements in the gamma energy range of 60 to 3,000 kiloelectron volts (keV) [Th-234 emits 93 keV gammas, and Pa-234m emits 1,080 keV gamma rays]; and (3) the average background rate of 12 microrad per hour and the > 35 pCi/gm DU exposure rate of 14.4 microrad per hour each provide sufficient counting statistics with the Ludlum instrumentation to acceptably measure these different dose rates because the Ludlum instrument has a sensitivity of 175 counts per minute (cpm) for one microrad per hour (2,100 cpm for 12 microrads per hour vs. 2,520 cpm for 14.4 microrads per hour).

4.3 RADIOLOGICAL CONTAMINATION STATUS

In this section, radiological contamination is documented for structures (Section 4.3.1), systems and equipment (Section 4.3.2), surface and subsurface soil (Sections 4.3.3 and 4.3.4), surface water and sediment (Section 4.3.5), groundwater (Section 4.3.6), and vegetation and biological resources (Section 4.3.7).

4.3.1 Structures

There are no radiologically contaminated structures within the JPG site. Facilities that were contaminated with DU were subject to a survey, remediation, and confirmatory survey after the remediation to verify that all remaining contamination is below NRC guideline levels (SEG 1995a). The only remaining residual contamination at JPG is the DU penetrators, which were fired into a target area of approximately 1,300 acres (5.3 km^2). No structures exist on the site that were used in conjunction with these DU penetrators. No structures are present in the DU Impact Area. Since the DU was only handled while loading one of three guns and fired into the impact area, there was no means of contaminating any structures on JPG.

4.3.2 Systems and Equipment

There are no radiologically contaminated systems and equipment within the JPG site. The only residual contamination at JPG is the DU penetrators, which were fired into a DU target area of 1,300 acres (5.3 km^2). No systems and equipment exist on the site that were used in conjunction with these DU penetrators. No systems and equipment are present in the DU Impact Area. Since the DU was only handled while loading one of three guns and fired into the impact area, there was no means of contaminating any systems and equipment on the JPG site.

4.3.3 Surface Soil

Residual contamination of surface soil has been investigated in the scoping and characterization surveys and in the ERM Program. Techniques used include measurement of exposure rates one meter above the ground surface in the scoping and characterization surveys and sample collection and laboratory analysis

in all three programs. The following paragraphs summarize the results of these programs (SEG 1995; SEG 1996; Ebinger and Hanson 1996).

4.3.3.1 Exposure Rate Measurements

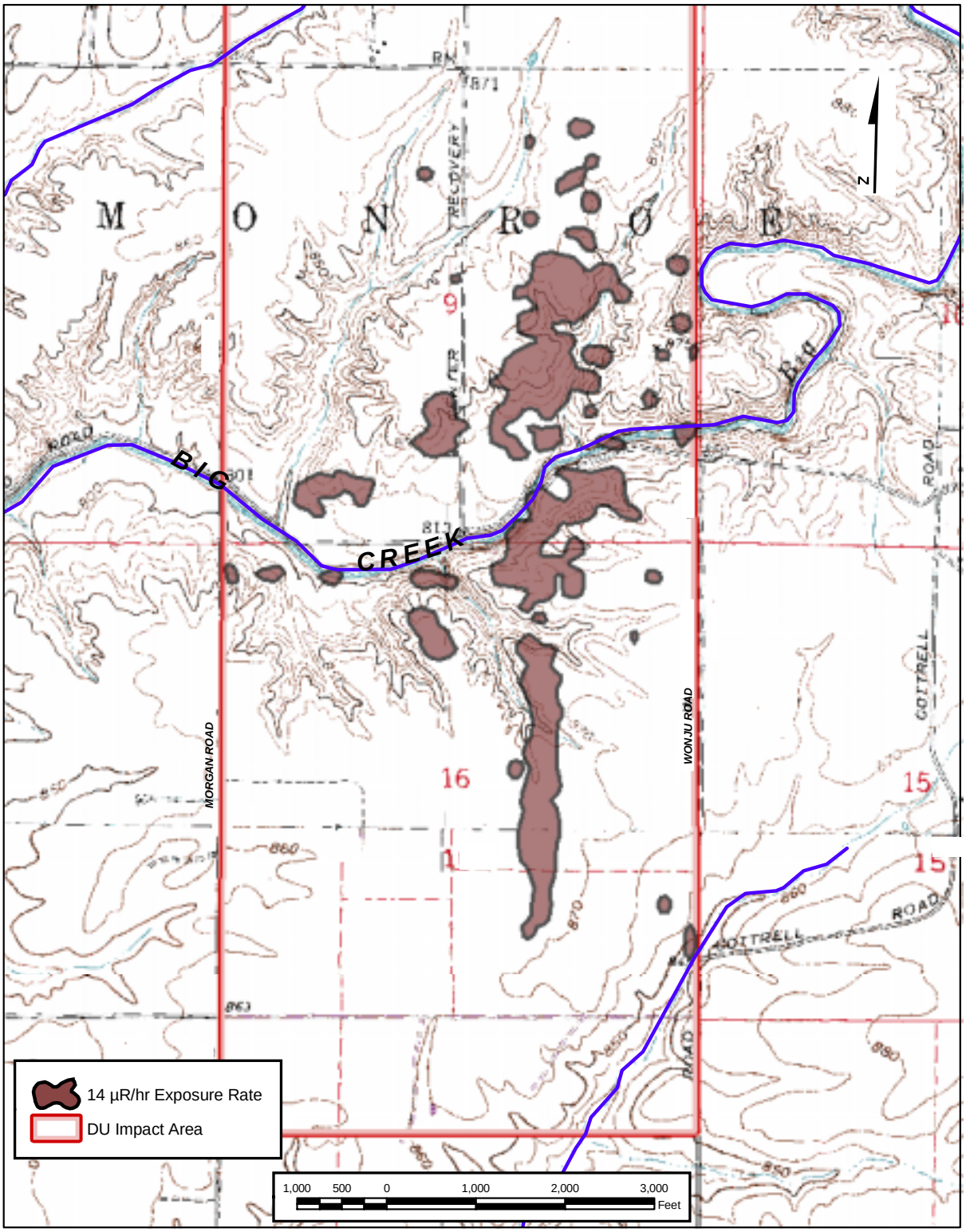
The scoping survey included measurement of exposure rates in an area south of the firing line and in the DU Impact Area. The background study was performed in 1995 prior to conducting measurements in the DU Impact Area. Thirty-five background measurements were taken south of the firing line in an unaffected area. An average background value of 12 μR/hr was established for this area consistent with background levels determined in 1983. Background values ranged from 6 to 8 μR/hr on roads and in creek beds to a high of 10 to 12 μR/hr in open fields and wooded areas (SEG 1995b). For approximately 25,000 measurements of exposure rate in the DU Impact Area, the majority (> 95 percent) of measurements were at background levels, but strong indications of the presence of DU were found near the trenches for each firing line. In these areas, exposure rates as high as approximately 3,300 μR/hr were observed.

During the characterization survey, a combination of exposure rate measurements, in situ gamma spectroscopy, and soil sampling was used to further define the affected area. The relationship between the average concentration of DU in the ground and exposure rate was analyzed to determine the isotopic concentration from the in situ gamma spectroscopy data. These measurements were obtained using the same instrument used in the scoping survey (SEG 1995b).

At each location, a single in situ gamma spectroscopy measurement yielded the total inventory of activity for each nuclide presented as an area of activity concentration at the surface. Using these results, the concentrations of Th-234 and Pa-234m were calculated for depth ranges of 0 to 5.9 in. (0 to 15 cm) 5.9 to 11.8 in. (15 to 30 cm), and 11.8 to 17.7 in. (30 to 45 cm) BGS. The specific assumptions used to determine this relationship are discussed in SEG (1996). Statistical analysis of the belowground soil uranium measurements (from Pa-234m data) resulted in a calculated average depth of contamination of 4.3 in. (11 cm) in the affected area. This value of 4.3 in. (11 cm) corresponds to a 95th percentile, that is, there is only a 5 percent chance that contamination would exist below 4.3 in. (11 cm). The exposure rate corresponding to a DU concentration of 35 pCi/g is 14.4 μR/hr based on a linear regression analysis of measured data. The contour map showing areas with an exposure rate greater than 14.4 μR/hr is shown in Figure 4-3.

4.3.3.2 Soil Samples

Sixty-two soil samples were collected during the scoping survey. Fifty samples were collected from within the DU Impact Area, and 12 samples were collected along the three trajectories between the firing line and C Road (Figure 4-1). The soil sampling program was unbiased and based on a 492-ft (150-m) grid system. Samples were collected along the 500 center firing position, along lines parallel to and 984 ft (300 m) east and west of the 500 center firing position, and along lines 1,968 ft (600 m) east and west, respectively, of the 500 center firing position.



Source: SEG 1996.

Figure 4-3. Exposure Rate of 14 µR/hr from Soil at Jefferson Proving Ground

The results of this sampling indicated that the highest uranium concentrations were detected south of Big Creek within the DU Impact Area. Total uranium concentrations ranged from < 1.3 to 201 pCi/g, with an average concentration of 12.9 pCi/g. Soil samples collected along the trajectories south of the DU Impact Area had concentrations ranging from 1.4 to1.8 pCi/g total uranium.

Soil samples were analyzed for concentrations of the three major uranium isotopes: U-234, U-235, and U-238. The U-238 to U-234 activity ratio (unitless) was reviewed to determine whether the uranium is naturally occurring or includes DU. In samples containing naturally occurring uranium, the activity ratio of U-238 to U-234 is approximately 1 (0.5 to 1.3). The activity ratio for DU is 5.5 to 9 based on a review of isotopic analysis of penetrators collected from the field within the DU Impact Area (SEG 1995b). Therefore, environmental measurements with U-238 to U-234 activity ratios greater than two are indicative of DU contamination.

The scoping survey soil samples indicated evidence of DU contamination primarily along the central and eastern trajectories within the DU Impact Area.

As part of the characterization survey, background surface and subsurface soil samples were collected from 10 sites in areas not impacted by the DU testing. The background locations were selected to ensure that these locations were representative of the different types of soils in the impact area and consistent with those locations sampled in 1983 as part of the baseline environmental impact survey. Background soil samples were collected from three depths at each location: 0 to 5.9 in. (0 to 15 cm), 5.9 to 11.8 in. (15 to 30 cm), and 11.8 to 17.7 in. (30 to 45 cm) BGS. Total uranium concentrations ranged from 1.33 to 2.76 pCi/g in the background soil samples as shown in Table 4-5. The U-238 to U-234 activity ratio in the background soil samples ranged from 0.5 to 1.3.

Table 4-5. Summary of Soil Sample Results for the Characterization Survey

Depth (cm) BGS	Number of Samples	Range in Total Uranium Concentration (pCi/g)	Average (pCi/g)
Background			
0–15	10	1.52–2.53	1.97
15–30	10	1.33–2.59	1.84
30–45	10	1.33–2.76	1.95
Penetrator Soil Samples			
0–15	20	2.9–12,318	2,881
15–30	20	1.5–547	79.5
30–45	20	1.8–63	12.7
45–60	13	1.4–11.5	4.50
Random Soil Samples			
0–15	20	1.46–4.73	2.60
15–30	20	1.51–6.91	2.40
30–45	20	1.34–4.21	2.00

Source: Compiled from SEG (1996).
To convert from centimeters to inches, divide by 2.54.
BGS = below ground surface.
cm = centimeter.
pCi/g = picocurie per gram.

To correlate measured soil uranium concentration with measured gamma dose rate, 26 measurements of dose rate for locations in and around a previously identified DU projectile impact trench in the affected area were made. The measured dose rates ranged from 10.0 μR/hr to 35.6 μR/hr with the resulting data analysis, using linear regression, correlating a 35 pCi/g DU concentration to a measured gamma dose rate of 14.4 μR/hr.

Analysis of surface soil samples collected in the ERM Program provides results consistent with the more detailed surveys. Most measurements show low levels of residual contamination, but high levels are found near the firing line trenches. Representative results are presented in Table 4-6.

Table 4-6. Representative Results for Soil Samples from the ERM Program

Sample Location	Concentration of Total Uranium (pCi/g)	
	Average	Range
6	45.0	0.8 to 225.1
8	172.2	0.78 to 3,857.0
10	15.5	0.03 to 106.7
12	5.7	0.03 to 37.1
26	1.3	0.3 to 1.8
32	1.3	0.2 to 1.9
43	1.0	ND to 1.0
44	1.4	ND to 2.1
45	8.8	0.3 to 63.0
46	3.1	0.1 to 5.2
47	1.0	0.1 to 1.6
48	4.9	0.14 to 40.9
53	1.2	0.23 to 1.6
56	3.0	0.23 to 15.0

Source: Ebinger and Hanson 1996.
ERM = Environmental Radiation Monitoring.
pCi/g = picocuries per gram.
ND = non-detect.

4.3.4 Subsurface Soil

Samples of subsurface soil were collected at 10 background, 20 randomly selected, and 20 penetrator locations during the characterization survey (SEG 1996). Sampling locations are summarized in Figure 4-2. In each case, samples were collected at depths of 0 to 15, 15 to 30, and 30 to 45 cm. For 13 of the penetrator locations, an additional sample was collected at a depth of 45 to 60 cm.

For the background sample locations, concentrations of total uranium ranged from 1.33 to 2.76 pCi/g and averaged 1.92 pCi/g. For the depth from 0 to 15 cm, the concentration of total uranium ranged from 1.52 to 2.53 pCi/g and averaged 1.97 pCi/g. For the depth from 15 to 30 cm, the concentration of total uranium ranged from 1.33 to 2.59 pCi/g and averaged 1.84 pCi/g. For the depth from 30 to 45 cm, the concentration of total uranium ranged from 1.33 to 2.76 pCi/g and averaged 1.95 pCi/g. The ratio of concentration of U-238 to U-234 ranged from 0.7 to 1.3. Trends of concentration or ratios of concentrations with location or depth are not evident.

For the randomly selected soil locations, the total uranium concentrations ranged from 1.34 to 6.91 pCi/g, with an average concentration of 2.33 pCi/g. None of the samples was from trenches within the DU Impact Area, and most samples were at background concentrations. The U-238 to U-234 activity ratio in the random soil samples indicated that 95% of the samples had uranium isotopic ratios within the range of natural variability (i.e., 0.5 to 2.0).

For penetrator locations, samples were collected at four depths. Concentrations of total uranium ranged from 1 to 12,318 pCi/g. The ratio of concentration of U-238 to U-234 ranged from 1.1 to 8.4. Results of the measurements are summarized in Table 4-7. Concentrations decreased with depth but indicated the presence of contamination and downward movement at all depths.

Table 4-7. Summary of Results of Surface and Subsurface Soil Analysis for Penetrator Locations

Depth	Concentration of Total Uranium (pCi/g)		
	Average	Range	
		Minimum	Maximum
0 to 15 cm	2,882	3	12,318
15 to 30 cm	80	2	547
30 to 45 cm	10	2	63
45 to 60 cm	5	1	12

Source: SEG 1996.
To convert from centimeters to inches, divide by 2.54.
BGS = below ground surface.
cm = centimeter.
pCi/g = picocurie per gram.

4.3.5 Surface Water and Sediment

Surface water and sediment samples have been collected as part of the scoping and characterization surveys and in the ERM Program. Results for each of these programs are presented in the following paragraphs.

4.3.5.1 Scoping Survey

For the scoping survey (SEG 1995a), concentrations in surface water were measured for samples collected at 14 locations. Concentrations of total uranium ranged from 0.21 to 4.11 pCi/L, and reported ratios of the concentrations of U-234 to U-238 were near unity. The data are summarized by location in Table 4-8. Concentrations are at background levels and show no trend with location.

Thirteen sediment samples were collected during the scoping survey. Four samples were collected from within the DU Impact Area, two samples were collected from Big Creek on the border of and east of the DU Impact Area border, five samples were obtained from the firing line trajectories south of the DU Impact Area, and two samples were collected on the western edge of the JPG where Big Creek and Middle Fork Creek exit the property. Samples collected upgradient of (2) and within (4) the DU Impact Area averaged 0.64 and 1.36 pCi/g of total uranium, respectively. Samples collected within the Firing Line Area (5) averaged 1.99 pCi/g of total uranium. Samples collected on the western perimeter averaged 1.46 pCi/g of total uranium. The maximum reported concentration was 3.08 pCi/g of total uranium for a location within the Firing Line Area. All concentrations and isotopic ratios are similar to background conditions.

Table 4-8. Average Concentrations of Total Uranium Measured in Surface Water in the Scoping Survey

Location	Concentration of Total Uranium (pCi/L)
Big Creek-Upgradient (2 locations)	0.27
Big Creek (4 locations)	1.53
North Tributary of Big Creek (2 locations)	0.75
Middle Fork Creek (4 locations)	0.46
South Tributary of Middle Fork Creek (2 locations)	0.58

Source: SEG 1995a.
pCi/L = picocuries per liter.

4.3.5.2 Characterization Survey

Surface water and sediment samples were collected from 10 locations during the characterization survey. Six samples were collected in Big Creek at locations upstream (1), within (4), and downstream (1) of the DU Impact Area. Four samples were collected in Middle Fork Creek at locations within (3) and downstream (1) of the Firing Line Area.

In the surface water of Big Creek, upstream of the DU Impact Area, the total uranium concentration was measured at 0.62 pCi/L; at locations within the DU Impact Area, the total uranium concentration in surface water ranged from 0.77 to 25.02 pCi/L. At the sample locations on the western boundary of the installation, the total uranium concentration in surface water averaged 0.89 pCi/L. The concentrations of total uranium in surface water samples collected from Middle Fork Creek ranged from 0.63 to 1.80 pCi/L. Concentrations of total uranium in sediment had the same trend as concentrations in surface water. The data are summarized in Table 4-9.

Table 4-9. Concentrations of Total Uranium in Surface Water and Sediment Measured in the Characterization Survey

Location Number	Location	Concentration of Total Uranium	
		Surface Water (pCi/L)	Sediment (pCi/g)
1	Big Creek, east boundary of JPG	0.62	0.78
2	Big Creek, DU Impact Area	25.0	6.20
3	Big Creek, DU Impact Area	2.92	3.83
4	Big Creek, DU Impact Area	0.77	2.18
5	Big Creek, DU Impact Area	1.08	0.75
6	Middle Fork Creek, Firing Line Area	1.04	3.10
7	Middle Fork Creek, Firing Line Area	0.73	2.23
8	Middle Fork Creek, Firing Line Area	1.80	3.46
9	Big Creek, west perimeter of JPG	0.89	0.75
10	Middle Fork Creek, west perimeter of JPG	0.63	1.81

Source: SEG 1996.
DU = depleted uranium.
JPG = Jefferson Proving Ground.
pCi/L = picocuries per liter.
pCi/g = picocuries per gram.

All samples were at, or near, background except for two sampling locations within the DU Impact Area. The surface water samples from the DU Impact Area that had higher total uranium concentrations were collected from static pools of water. The U-238 to U-234 activity ratios in the samples from static pools of water were 4.4 and 7.3, indicating the presence of DU contamination. Uranium isotopic ratios were within the range of natural variability for 7 of the 10 surface water samples.

4.3.5.3 Environmental Radiation Monitoring Program

Data for concentrations of uranium isotopes in surface water and sediment are reported for eight locations along Big Creek and Middle Fork Creek. Results are similar and are represented by the data summarized in Table 4-10 for sampling points located on Big Creek at the west edge of the DU Impact Area and Middle Fork Creek at the west edge of the Firing Line Area. High concentrations are reported for the year 1991 but are not repeated for following years, implying a handling, measurement, or reporting error. Ratios of the concentrations of U-234 to U-238 are within the naturally occurring range for all measurements.

Table 4-10. Concentrations of Total Uranium in Surface Water and Sediment Reported for the ERM Program

Year	Average Concentration of Total Uranium			
	Big Creek		Middle Fork Creek	
	Surface Water (pCi/L)	Sediment (pCi/g)	Surface Water (pCi/L)	Sediment (pCi/g)
1984	0.18	0.23	0.02	0.94
1985	0.24	–1	0.07	–
1986	0.58	0.61	0.29	–
1987	0.48	0.18	0.47	1.14
1988	0.50	0.23	0.37	1.67
1989	0.30	0.08	0.0	0.59
1990	3.32	0.33	2.45	0.40
1991	17.73	0.62	4.75	3.09
1992	1.33	0.14	0.09	0.39
1993	0.49	0.28	0.0	0.84
1994	0.33	4.55	0.0	1.87

Source: Ebinger and Hansen 1996.
– = no data.
ERM = Environmental Radiation Monitoring.
pCi/g = picocuries per gram.
pCi/L = picocuries per liter.

4.3.6 Groundwater

Concentrations of uranium isotopes in groundwater have been measured at 11 wells in the scoping and characterization surveys and in the ERM Program. As reported in the introduction to this section, the scoping and characterization survey samples were collected in 1994 and 1995. A summary of the results of these measurements is presented in Table 4-11. The total uranium concentration in groundwater samples collected in the surveys ranges from 0.33 to 5.09 pCi/L at background levels at the site. The U-238 to U-234 activity ratio in groundwater samples indicates that the uranium is naturally occurring.

Table 4-11. Summary of Concentrations of Uranium in Groundwater Samples from the Scoping and Characterization surveys

Sample Location	Concentration of Total Uranium (pCi/L)	
	Scoping Survey	Characterization Survey
MW-01	0.43	0.33
MW-02	1.25	1.20
MW-03	0.76	1.67
MW-04	2.40	3.34
MW-05	0.46	3.74
MW-06	3.61	5.09
MW-07	1.99	0.80
MW-08	1.23	1.10
MW-09	2.26	1.50
MW-10	3.38	1.34
MW-11	<1.28	2.04

Source: SEG 1995a and 1996.
MW = monitoring well.
pCi/L = picocuries per liter

The 11 wells discussed above are also sampled as part of the ERM Program. Two of the monitoring wells (MW-3 and MW-7) are located near the firing line approximately 1.9 miles (3 km) south of the DU Impact Area. Seven of the wells are located in the vicinity of Big Creek, and results of measurements have been reported for these wells.

For well MW-11, located near Big Creek at the west of the DU Impact Area, concentrations of total uranium were below approximately 5 pCi/L for the years 1988 through 1993. For well MW-5, located near Big Creek at the west of the DU Impact Area, concentrations of total uranium approached 15 pCi/L for the year 1990 and were below approximately 5 pCi/L for the years 1990 through 1993. For well MW-9, located near Big Creek at the center of the DU Impact Area, concentrations of total uranium ranged from 5 to 15 pCi/L for the years 1988 through 1993. For well MW-1, located near Big Creek at the east side of the DU Impact Area, concentrations of total uranium were approximately 5 pCi/L for years 1988, 1989, 1990, 1992, and 1993 but rose to approximately 35 pCi/L in 1991. Behavior similar to that of well MW-1 is reported for well MW-10, except that the peak in concentration of total uranium of approximately 80 pCi/L occurred in 1992. The results indicate that groundwater conditions may be affected by DU. The accuracy of these high values for the years 1991 and 1992 is in doubt due to QA issues at the analytic laboratory. Deletion of the high values is supported by review of trends of the data and analysis of duplicate samples (see appendix C and Ebinger and Hanson 1996).

4.3.7 Vegetation and Biological Resources

Sampling data for vegetation and biological specimens are summarized in Sections 4.3.7.1 and 4.3.7.2, respectively.

4.3.7.1 Vegetation Samples

During the scoping survey, 20 vegetation samples were collected. Fourteen samples were obtained from within the DU Impact Area, and six samples were obtained along the firing line trajectories. The total uranium concentration in vegetation samples was less than 0.7 pCi/g in all samples. Two lichen samples

from the south-central portion of the DU Impact Area had U-238 to U-234 activity ratios of 2.3 and 2.6, which indicate DU contamination.

During the characterization survey, 10 vegetation samples of lichens, leaves, or grasses were collected from the affected area trenches. Samples were collected from the three penetrator fragment areas shown on Figure 4-2. Five vegetation samples were collected from Area 1, four samples from Area 2, and one sample from Area 3 and were analyzed for total uranium. Samples were washed with deionized water prior to analysis, and the wash water was analyzed separately from the vegetation sample to determine the amount of uranium on the surface of, and in, the sample. The total uranium concentration in vegetation samples ranged from 0.75 to 3,447 pCi/g, with an average concentration of 627.5 pCi/g. The total uranium concentration in the root wash samples ranged from 46.1 to 14,258 pCi/g, with an average concentration of 2,869 pCi/g. The U-238 to U-234 activity ratio ranged from 6.1 to 8.4, indicating the presence of DU contamination.

As part of the ERM Program, analyses of eight lichen samples and seven leaf samples have been reported. For 16 of the samples concentrations of total uranium were less than 2 pCi/g but were at 91 pCi/g for the final sample (lichen). The results indicate that uranium can concentrate in vegetation but that this has not occurred on a widespread basis.

4.3.7.2 Biological Samples

During the characterization survey, a total of eight biological samples were collected from deer, freshwater clams, fish, and a soft-shelled turtle. For three deer samples, concentrations of total uranium ranged from 0.09 to 0.42 pCi/g. For two samples of freshwater clams, concentrations of total uranium were 0.33 and 0.77 pCi/g. Concentrations of total uranium in fish and turtle were below 0.25 pCi/g. The U-238 to U-234 activity ratio ranged from 0.4 to 1.2 and does not indicate the presence of DU contamination.

Data on concentrations of uranium in deer are reported for the ERM Program for the years 1984, 1987, 1992, and 1993. Concentrations of total uranium are low, less than 0.4 pCi/g, and do not indicate an impact from DU.

4.4 SUMMARY

In 1994 and 1995 characterization studies, remediation and final survey of radiological status were completed for facilities and grounds located south of the firing line. The characterization activities identified several facilities in which DU contamination from handling DU projectiles was greater than allowable NRC limits. After remediation, a final survey confirmed that these facilities were decontaminated to the extent that any measured radioactivity was well below applicable NRC limits for uranium, beta emitters, and gamma radiation. In addition, the survey confirmed that the three gun-firing positions themselves were not contaminated with DU in excess of that allowed under NRC regulations and limits applicable at that time.

In 1994 and 1995, SEG conducted a radiological scoping survey and a radiological characterization survey of the DU Impact Area of the JPG that was affected by the firing of about 220,462 lbs (100,000 kg) of DU projectiles between 1983 and 1994. The primary result of the scoping survey of the DU Impact Area was identification of the affected area within the larger firing range. The affected area of about 125 acres (12.5 km^2) was determined by measurements of DU concentrations in the soil in excess of the level of 35 pCi/g of uranium.

The characterization survey was performed to obtain more detailed information regarding the location and extent of DU contamination in the affected area of 125 acres (12.5 km^2), which was previously identified by the scoping survey. A total of 235 environmental samples, including soil, surface water, groundwater, sediment, vegetation, and animals, were obtained and measured for DU concentration. Soil samples included depths of up to 17.7 in. (45 cm), as well as samples from the affected DU trajectory area including soil directly under extant DU penetrators. Uranium isotope concentrations were measured, and the U-238/U-234 activity ratio was calculated for each measurement. Together, the magnitude of uranium concentration and the U-238/U-234 ratio constitute a determination of the extent and nature of any uranium contamination.

Using the correlation of 14.4 μR/hr as the indicator of greater than 35 pCi/g DU soil contamination, the characterization survey identified specific regions within the affected area that are in excess of this concentration. Only two affected area surface water measurements, for stagnant water pools, exceeded guidelines proposed for uranium in water. In addition, surface water samples collected from Big Creek and Middle Fork Creek on a monthly basis for the year 2001 by the Indiana State Department of Health (ISDH 2002) indicate the presence of only background levels of radioactivity. Concentrations of uranium were high for soil in and around actual DU penetrator locations in the affected area. The characterization survey also identified that the top 4.3 in. (11 cm) of soil in the affected area would exceed the 35 pCi/g of uranium concentration level based on a 95th percentile analysis of the measurements of DU in soil at different depths. Another result of the characterization survey was that, with the exception of vegetation, all biological samples obtained from the DU affected area (i.e., animals) showed no radiological evidence of DU contamination by virtue of both the magnitude of uranium concentration and the U-238/U-234 activity ratio.

In summary, the radiological scoping and characterization surveys identified the specific areas within the JPG that are contaminated with DU above 35 pCi/g and provided information on the extent of movement of uranium through the environment. The scoping survey identified a 125-acre (12.5-km^2) area within the potentially affected area as being DU contaminated. A common result of the scoping and characterization surveys is that soil samples collected in the immediate vicinity of, or immediately below, penetrators contain relatively high levels of DU and that soil samples collected in locations not in the immediate vicinity of penetrators contain low or background levels of uranium. In addition, surface water and wildlife samples contain background levels of radioactivity. These results indicate that residual contamination at the JPG is concentrated in a heterogeneous manner in trenches located along the three firing lines and that movement of DU through the environment has been confined to the immediate vicinity of the penetrators.

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5.0 DOSE ANALYSIS

Residual radiological contamination at JPG is in the form of DU penetrators and their degradation products concentrated in a heterogeneous manner in and around trenches oriented along three northward-directed firing lines. A large amount of UXO is co-located with the residual contamination, posing an immediate risk to life in addition to the lesser, long-term stochastic risk posed by the residual radiological contamination.

The operating history and radiological status of the facility are discussed in greater detail in Sections 2.0 and 4.0 of this DP. As described in Section 6.0 of this DP, the proposed action is license termination under restricted conditions. The objective of this section is to describe dose analysis that provides reasonable assurance that the dose criteria of 10 *CFR* 20.1403(b) and (e) will not be exceeded. The dose analysis demonstrates that if institutional controls remain in effect, dose to the average member of the critical group (AMCG) will not exceed 25 mrem/yr, and if institutional controls are not in effect, dose to the AMCG will not exceed 100 mrem/yr.

The dose analysis follows the first approach of Section 5.0 of the NMSS Decommissioning SRP (NRC 2000), i.e., the analysis uses projections of the final concentrations of residual contamination to demonstrate compliance with the dose criteria. Given the proposed approach to license termination (Section 6.0), values for DCGLs are not calculated. Compliance with the ALARA, financial assurance, and public participation requirements of 10 *CFR* 20.1403 are presented in Sections 7.0, 15.0 and 16.0 of this DP. The balance of this section, sub-sections 5.1 through 5.8, describes the technical approach, conceptual site model (CSM), source term, transport pathways, receptors, exposure scenarios, analysis techniques, and results and findings of the dose analysis.

5.1 TECHNICAL APPROACH TO DOSE ANALYSIS

The technical approach to dose analysis is development and analysis of exposure scenarios. A scenario is a combination of source conditions, environmental transport pathways, and receptor locations and behavior that constitute a hazard to health. The starting point for development of scenarios is review of current conditions of the site, plans for future use or development of the site, and regulatory guidance on dose analysis.

Source conditions include the characteristics of the residual contamination and environmental conditions that facilitate, or cause, release of the material to the environment. Environmental conditions include physical and chemical characteristics of environmental media; that is, soil, groundwater, surface water, and the meteorological, hydrologic, and geomorphologic processes that transport radioactive material to receptors. Environmental and radiological status of the site is described in Sections 3.0 and 4.0 of this DP. Plans for future use of the site are described in Section 6.0, and the primary source of regulatory guidance for dose analysis was Appendix C of the SRP for license termination (NRC 2000).

The approach to the dose analysis is represented schematically in Figure 5-1. The figure represents only estimations of dose and findings on compliance with dose criteria. Additional requirements of the framework for license termination are described in NRC (2000); ALARA analysis, financial assurances, and public participation are discussed in Sections 7.0, 15.0 and 16.0 of this DP. The following sub-sections describe the elements of the procedure for estimation of dose and the findings on compliance with dose criteria.

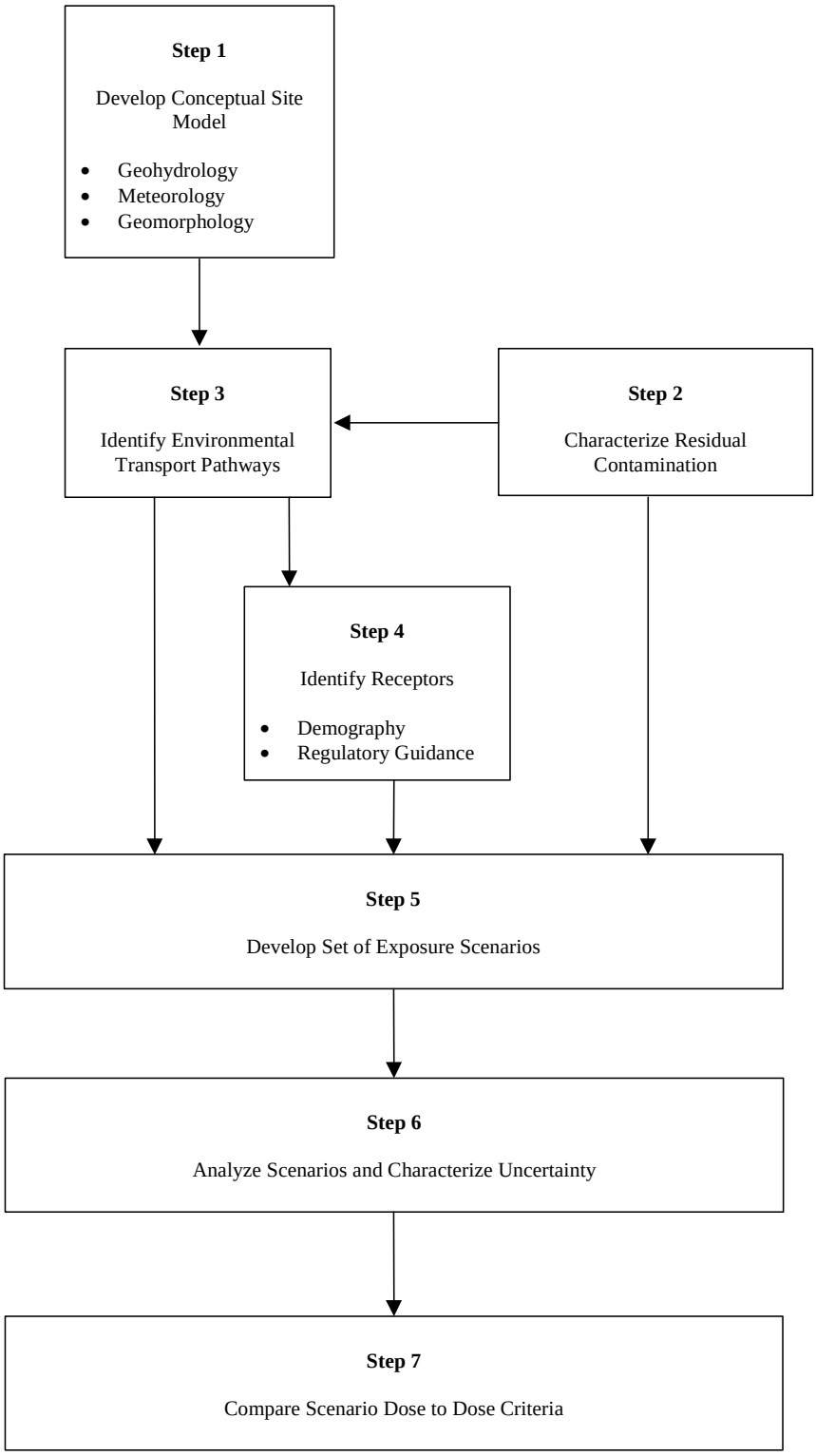

Figure 5-1. Schematic Representation of Procedure for Estimation of Dose

5.2 CONCEPTUAL SITE MODEL

The CSM is an abstraction from the observed physical conditions and processes of the site that provides a basis for estimation of rates of mobilization and movement through the environment of residual contamination. Details of the basis for development of the CSM for JPG are presented in Section 3.0 of this DP and in an EIS prepared for the decision on disposition of JPG (U.S. Army 1991). The primary elements of the CSM are abstractions of the meteorological, geologic, hydrologic, and geomorphological processes affecting the site. The following paragraphs discuss each of these elements of the model.

Climatic conditions in the vicinity of the JPG are moderate with winter temperatures ranging from 22 to 35°F (–6 to 2°C) during the winter and 75 to 85°F (21 to 27°C) during the summer. Annual precipitation is approximately 43 in. (109 cm), and annual average wind speed is approximately 8 mi/hr (4 m/s). Tornadoes occur in the vicinity of the JPG but because of the absence of contaminated buildings, the dispersed nature of the residual soil contamination, and the extreme mixing characteristic of tornadoes, tornadoes are not included in the CSM.

Geohydrologic conditions at the site include physical properties of soils and groundwater and surface water flow characteristics. In addition, rates of erosion related to precipitation and run-off are included in the CSM. Stratigraphy at JPG is represented as comprising two layers, glacial till overlying limestone bedrock. Thickness of the till is approximately 20 ft (6 m), and the texture is that of a silt loam. Hydraulic conductivity for this type of soil ranges from 0.1 to 980 m/yr (0.3 to 3,200 ft/yr) with an average of approximately 30 m/yr (100 ft/yr) [Meyer and Gee 1999]. Results of a limited number of slug test measurements of hydraulic conductivity of glacial till at JPG are consistent with the average values for silt loam. Thus, the average hydrologic properties for silt loam were adopted as representative of JPG conditions for the contaminated unsaturated and saturated zones.

Depth to the water table for on-site wells is reported as approximately 3 m (10 ft). The limestone bedrock underlying the site contains fractures and solution cavities. Wells completed in the bedrock formation are productive and serve as a source of domestic/household water for some residents in the vicinity of JPG. In general, well water is not used for irrigation in the vicinity of the site. Well depths range from 13 to 60 m (40 to 200 ft) [IDNR 2001].

The primary source of drinking water for residents in the vicinity of JPG is municipal water drawn from the Ohio River. Average flow rate for the Ohio River near the JPG is 1.44×10^5 ft^3/s (1.29×10^{11} m^3/yr). Drainage of surface water from the JPG is toward the west (toward the East Fork of the White River). Annual average flow for this river near Bedford, Indiana, is 4,184 ft^3/s (3.74×10^9 m^3/yr) [USGS 2002].

The risk of earthquake at JPG is dominated by events at the NMZ. Peak ground acceleration at JPG due to an earthquake with a 1,000-year return period is estimated as 0.047% g. An event of this magnitude is not expected to disturb near-surface soils or hydraulic conditions in the bedrock aquifer; therefore, earthquakes are not included in the CSM.

The portion of the JPG containing residual contamination, the DU Impact Area, is drained by Big Creek. Measurements of flow rate and loading of suspended sediment have not been conducted for this stream. Estimates of run-off to Big Creek and erosion rates for the Big Creek basin are based on hydrologic and geomorphologic modeling. Base data included a digital elevation model of the basin and rainfall amounts for storms of 2-, 10-, 25-, 50- and 100-year return periods. The HEC-1 (Hydrologic Engineering Center) [i.e., a Hycomputer code developed by the U.S. Army Corps of Engineers (USACE)] and the TR-55 computer code developed by the Soil Conservation Service (SCS) were used to simulate surface water flow hydrographs and run-off quantities, respectively. Analysis of sediment loading for a similar basin,

Brush Creek, Indiana, was used to estimate sediment yield for the Big Creek basin. Annual average flow and sediment yield for Big Creek near the western boundary of JPG were estimated as 124×10^6 ft^3/yr (3.52×10^6 m^3/yr) and 2,320 lbs/acre/yr (2.60 MT/ha/yr), respectively. The procedure for estimation of these quantities is discussed in detail in Attachment 1 to Appendix C of this DP. The sediment yield corresponds to a basin averaged erosion rate of 0.0005 ft/yr (0.016 cm/yr).

5.3 CHARACTERIZATION OF SOURCE TERM

The objective of this section is to conceptualize the source term based on site characterization and regulatory guidance. This source term serves as a reasonably conservative basis for estimation of impacts. This conceptualization uses current conditions but is not intended to represent these conditions.

The original form of residual contamination at JPG is DU metal penetrators shaped as long, narrow rods. During firing, the penetrators struck the ground and, in some cases, broke into pieces before lodging in place. The angles of fire are such that most of the penetrators are thought to be located near the surface. Mass balance based on inventory control and recovery programs indicates that approximately 154,000 lbs (70,000 kg) of DU remain in the DU Impact Area. Primary constituents of the penetrators are the uranium isotopes U-234 and U-238 with a specific activity of 3.8×10^{-7} Ci/g. Trace contaminants include Pu-238/239/240 and technetium-99 (Tc-99) at concentrations less than 5 and 540 pCi/g, respectively.

The residual contamination is concentrated in and around trenches oriented along three lines of fire. The area of significant contamination is estimated as approximately 125 acres (5×10^5 m^2) although the range of estimates extends to approximately 250 acres (1×10^6 m^2). A schematic of the contaminated area is presented in Figure 4-3. Although intact penetrators and fragments of penetrators are visible, analysis of soil collected in the immediate vicinity of penetrators shows high levels of uranium, indicating that degradation is occurring. This finding is consistent with studies of corrosion of DU (Royal Society 2002), indicating that penetrators in intimate contact undergo complete degradation on the order of decades.

A final element used for identification of source characteristics is regulatory guidance (NRC 2000) recommending mixing of surface as may occur when the site is prepared for construction or plowed for agricultural purposes. The recommended mixing depth that maximizes concentration is 6 in. (15 cm).

Based on the concentration levels and potential for degradation described above, two cases of source characteristics are developed. In the first case, uranium at a concentration of 225 pCi/g is distributed over an area of 124 acres (5×10^5 m^2) to a depth of 6 in. (15 cm). In the second case, uranium at a concentration of 94 pCi/g is distributed over an area of 247 acres (1×10^6 m^2) to a depth of 6 in. (15 cm).

5.4 IDENTIFICATION OF ENVIRONMENTAL TRANSPORT PATHWAYS

Environmental pathways of potential significance at JPG include direct transport of energetic particles or electromagnetic radiation; atmospheric dispersion of resuspended soil particles; transport in groundwater or surface water; and accumulation in plants, domestic animals, or wildlife. Each of these seven processes may occur in the near field, affecting receptors in the immediate vicinity of the residual contamination or may occur over greater distances. At JPG, atmospheric dispersion and transport in groundwater and surface water occur over both short and long distances while the remaining processes occur only over the short distances.

Because residual contamination is not in gaseous form, atmospheric transport involves resuspension and dispersion of soil particles. Because of the near-surface nature of residual contamination at JPG, redistribution of contamination by insects or burrowing animals is not important. In addition to the seven

environmental transport pathways, a human activity-mediated pathway, direct contact, is considered. Thus, a total of eight major pathways for movement of residual contamination to receptors are identified for exposure scenario development. Sub-pathways may be identified for some or all of the identified pathways but are omitted from the discussion to facilitate presentation of key concepts. Sub-pathways entering each of the scenarios are described in Appendix C.

5.5 SELECTION OF RECEPTORS

Selection of receptors for dose analysis involves consideration of site conditions and regulatory guidance. Because the proposal for JPG is license termination with restriction, two cases are considered. In the first case institutional controls are assumed effective, while in the second case institutional controls are assumed to fail.

To bound and provide perspective on potential impacts, a set of receptors is constructed for each case. For the case where institutional controls remain in effect, the activities and locations of the set of candidate receptors (i.e., actual residents and individuals) are constrained by institutional controls. For the case in which institutional controls fail, the set of candidate receptors is expanded to include hypothetical individuals whose locations and activities are not possible currently. Consistent with regulatory requirements, each candidate receptor is a member of the group of individuals reasonably expected to receive the greatest exposure to residual contamination. Location and behavior are factors defining this individual, termed the AMCG. For each of the two institutional control cases, identification of the AMCG involves consideration of the:

- condition and location of residual contamination,
- proposed activities for the site,
- release mechanisms and environmental transport pathways significant to the site,
- current distribution of nearby residences and the surrounding population, and
- regulatory guidance.

The following sections discuss selection of on-site and off-site receptors for the two cases.

5.5.1 Institutional Controls in Effect

The proposed action for JPG involves transfer of control of the site to the FWS and the USAF for the foreseeable future. Under this proposed action, the USAF will use a portion of the JPG as a bombing range and will prohibit public access to the site. The mission of the FWS is to manage lands for the conservation of fish, wildlife, and plants. In this mission, the FWS plans to provide limited/restricted public access for fishing, hunting, and wildlife observation to certain areas north of the firing line (see Appendix A to this DP). Because of the hazard of UXO at the site, access to these activities will be controlled, and these controls are incorporated into the process for identification of candidate AMCGs where institutional controls remain in effect.

Controls include limitation of fishing to Old Timbers Lake and of wildlife observation to locations north of K Road. Because these locations are upgradient and removed for the area of residual contamination, these individuals are removed from consideration as an AMCG. The FWS plans to allow hunters access to portions of the JPG near but not on the area having residual contamination for two time periods each year. Proximity of the hunters and access of the wildlife to the DU Impact Area introduces the potential for exposure to residual contamination. Thus, a hunter of deer and turkey is selected as an AMCG for on-

site receptors. In addition to members of the public, FWS and USAF/INAG personnel may be in close proximity to the DU Impact Area. This proximity introduces the potential for exposure to residual contamination; therefore, an on-site worker frequenting the vicinity of the DU Impact Area is selected as an AMCG.

For the case where institutional controls remain in effect, selection of AMCGs located off-site is based on consideration of the location of nearby individuals and population centers in relation to the residual contamination and environmental transport mechanisms and pathways. The release mechanism of residual contamination and environmental transport pathways at JPG is atmospheric dispersion of resuspended soil, dissolution and movement in groundwater, and suspension in run-off and surface water. Although nearby residents currently do not use Big Creek as a source of domestic water, transport of sediment in surface water may influence these residents; therefore, these individuals are selected as an AMCG. Because light industrial activity occurs in the vicinity of JPG, an off-site worker is selected as an AMCG. Surface water draining from the DU Impact Area flows to the west, with the East Fork of the White River as the nearest significant location for public use. Residents of the town of Bedford, Indiana, located near this river, are selected as AMCGs for population exposures based on these considerations.

5.5.2 Institutional Controls Failed

If institutional controls fail, individuals would continue to use the JPG for hunting, fishing, and recreation. In addition, these individuals could perform these activities in the DU Impact Area or, in an extreme case, establish a residence and farm. These on-site activities are unlikely because of the presence of UXO; however, this case is assessed to bound the potential impacts. Locations and activities of the individuals where institutional controls fail are selected on the basis of the current residential activity and regulatory guidance.

Given the potential for fishing in the vicinity of Big Creek, an on-site fisherman is selected as an AMCG but conditions remain the same as in the case of intact institutional controls. Similar to the case where institutional controls remain in effect, an on-site hunter is selected as an AMCG; however, in this case, the hunter is permitted to enter the DU Impact Area. Consistent with local farming activities and regulatory guidance, a residential farmer located in the DU Impact Area is selected as an AMCG. Behavioral variations of this case are considered, farming with and without the use of irrigation water and domestic residency on full- and part-time basis.

For off-site receptors, failure of institutional controls does not affect residual contamination, release mechanisms, environmental transport pathways, or receptor locations and activities. Therefore, the off-site individual resident and off-site worker located near the site and the individual located near Bedford, Indiana, also are identified as AMCGs when institutional controls fail.

5.6 SELECTION OF EXPOSURE SCENARIOS

Development of exposure scenarios involves combining source conditions, transport pathways, and receptor locations and activities for the cases of effective and ineffective institutional controls. The discussions of Sections 5.3, 5.4 and 5.5 identified source conditions (2), transport pathways (8), and receptors (5 or 6) for the two institutional control cases. Combining these elements produces 64 and 80 scenarios for the cases of effective and ineffective institutional controls, respectively.

The sets of scenarios are screened to avoid unnecessary complexity and focus attention on important issues. Screening based on the location and activity of receptors described in the selection of receptors (Section 5.5) reduces the sets of scenarios to 14 and 24 for the cases of effective and ineffective institutional controls, respectively. Screening based on bounding of impacts and perspective of pathways

is used to remove the off-site industrial worker for whom impacts are bounded by both off-site and on-site scenarios. No additional pathways are introduced for this off-site industrial worker.

Finally, the list of scenarios is reduced by combination of single pathway scenarios affecting a common receptor into single multi-pathway scenarios. This screening process resulted in the final set of scenarios. These scenarios include: six scenarios for effective institutional controls and five scenarios for the case of ineffective institutional controls. Conditions for the final set of scenarios are summarized in Tables 5-1 and 5-2 for the cases of effective and ineffective institutional controls, respectively.

Table 5-1. Summary of Exposure Scenarios, Effective Institutional Controls

Receptor	Location	Transport Pathway[a]
Hunter	On-site	Wildlife
Worker	On-site	Direct Atmospheric Dispersion
Fisherman	Off-site	Surface water
Residential farmer	Off-site	Surface water
Industrial worker	Off-site	Groundwater
Population	Off-site	Surface water

[a]Pathways listed are primary pathways and may invoke a further set of sub-pathways.

Table 5-2. Summary of Exposure Scenarios, Institutional Controls Ineffective

Receptor	Location	Transport Pathway[a]
Hunter	On-site	Wildlife Direct Atmospheric Dispersion
Fisher	On-site	Surface water
Residential farmer (four versions)	On-site	Direct Atmospheric Dispersion Groundwater Plants Domestic Animals Contact
Residential farmer	Off-site	Surface water
Population	Off-site	Surface water

[a]Pathways listed are primary and may invoke sub-pathways. For example, primary pathways for on-site residential farmer are sub-pathways for off-site residential farmer.

5.7 ANALYSIS OF EXPOSURE SCENARIOS

Analysis of exposure scenarios developed for JPG requires estimation of release rate to and transport through environmental pathways, as well as evaluation of impacts attributable to a variety of receptor behavior-dependent exposure modes. This section describes the calculation techniques, including analysis of sensitivity and uncertainty, used for evaluation of JPG scenarios.

5.7.1 Techniques for Estimation of Dose

Doses for JPG scenarios were estimated using a combination of the RESRAD (LePoire et al. 2000) computer model and hand calculations. Version 6.1 of RESRAD was used to simulate hunter, worker, and residential farmer scenarios. Detailed discussion and a listing of parameter values are presented in Appendix C for RESRAD analyses. Values of the most important parameters are presented below in the discussion of sensitivity and uncertainty analysis.

The hand calculations were used to simulate doses due to potential contamination of surface water by erosion of the DU Impact Area. Drinking water dose was calculated as the product of concentration of uranium in water, water intake rate (510 L/yr), and dose conversion factor for ingestion (2.6×10^5 rem/Ci). Dose due to ingestion of fish was calculated as the product of concentration of uranium in water, bioaccumulation factor for uranium in fish [(10 pCi/kg)/(pCi/L)], fish consumption rate (15 kg/yr), and dose conversion factor for ingestion. Using the value of erosion rate of 2,320 lbs/acre/yr (2.60 MT/ha/yr) discussed above in Section 5.2, a value of 0.036 Ci/yr was estimated for the release rate of uranium to Big Creek due to erosion.

5.7.2 Sensitivity and Uncertainty Analysis

Doses predicted using environmental transport and exposure mode models depend, in a complex manner, on future societal conditions, changes in human behavior and environmental conditions and processes, the nature of the models, and the values of parameters used in the models. Changes in societal conditions and human behavior cannot be estimated accurately. This uncertainty is accounted for by using a reasonably conservative set of exposure scenarios. Evaluation of uncertainty related to model structure is not currently possible and is addressed by use of simple models whose performance is based on reasonably conservative understanding of transport and exposure processes. Evaluation of the uncertainty related to values of the parameters is addressed using deterministic sensitivity analysis and Monte Carlo simulation based on available data on parameter distributions.

Sensitive parameters in the JPG dose analysis were identified by calculation of single point sensitivity coefficients using repeated runs of the RESRAD computer code. This analysis identified the distribution coefficient for uranium in contaminated zone soil, mass loading factor, and drinking water ingestion rate as the most sensitive parameters. Uncertainty analysis using the RESRAD code was then performed for residential farmer and hunter scenarios using parameter distributions based on literature and regulatory guidance. For the distribution coefficient of uranium in contaminated zone soil, a triangular distribution was selected. The minimum, median, and maximum values were 5, 50, and 60 mL/g, respectively. For mass loading factor, a uniform distribution with minimum and maximum values of 6.3×10^{-9} and 6.2×10^{-8} lb/ft^3 (0.0001 and 0.001 g/m^3) was selected. A uniform distribution was also selected for drinking water ingestion rate with minimum and maximum values of 116 and 174 gal/yr (440 and 660 L/yr).

5.8 RESULTS OF DOSE ANALYSIS

Doses estimated for the case where institutional controls remain in effect and based on a source concentration of 225 pCi of uranium per gram of soil are presented in Table 5-3. The largest peak dose (6.4 mrem/yr) is estimated for the off-site worker, with the majority of impact due to ingestion of drinking water. For the off-site residential farmer, the peak dose from external exposure and inhalation also is observed in the early years, but lower doses from ingestion of water and consumption of crops appear in later years (i.e., after year 200). In all scenarios, doses are below the 25 mrem/yr criterion of 10 *CFR*

Table 5-3. Doses for Scenarios with Institutional Controls in Effect[a]

Receptor	Location	Dose (mrem/yr)	Method
Hunter	On-site	2.0	RESRAD
Worker	On-site	2.9	RESRAD
Fisherman	Off-site	0.81	Hand Calculation
Residential farmer	Off-site	0.2	RESRAD
Industrial worker	Off-site	6.4	RESRAD
Population	Off-site	0.003	Hand Calculation

[a]Doses for RESRAD simulations are peak-of-the mean estimates from probabilistic calculations. Doses for hand calculations are deterministic values.

20.1403(b). Estimated doses scaled linearly with source concentration. Therefore, the dose due to the source at 94 pCi/g was reduced relative to the dose for the case of source at 225 pCi/g in proportion to the ratio of source concentration. Dose due to fish consumption on Big Creek was estimated as approximately 0.81 mrem/yr. The population dose from the consumption of drinking water by the population of Bedford, Indiana, is 0.04 person-rem/yr.

Doses estimated where institutional controls fail and based on a source concentration of 225 pCi of uranium per gram of soil are presented in Table 5-4. No credit is taken for a period during which institutional controls are maintained. The largest peak dose (37 mrem/yr) is estimated for the on-site residential farmer, with the majority of dose from external exposure and inhalation occurring soon after the controls fail. Slightly lower doses from drinking water and crop ingestion occur approximately 200 years after failure of institutional controls. In all cases, doses are below the 100 mrem/yr criteria of 10 *CFR* 20.1403(e). Sensitivity analysis of the on-site residential farmer scenario indicated that the presence of trace contaminants, Pu-238/239/240 and Tc-99 would increase dose by approximately 0.15 mrem/yr, less than 0.5 % of the dose due to uranium for that scenario.

Table 5-4. Doses for Scenarios with Failure of Institutional Controls[a]

Receptor	Location	Dose (mrem/yr)	Method
Hunter	On-site	3.6	RESRAD
Fisherman	On-site	0.81	Hand calculation
Residential farmer	On-site	37.0	RESRAD
Residential farmer	Off-site	0.2	RESRAD
Population	Off-site	0.003	Hand Calculation

[a]Doses for RESRAD simulations are peak-of-the mean estimates from probabilistic calculations. Doses for hand calculations are deterministic values.

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